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A system dynamic approach to manage changeability in manufacturing systems

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Abstract

This paper addresses the challenges in managing variety and volume in changeable manufacturing systems. A dynamic model is presented to better understand and analyse the dynamic of the strategic decisions concerning manufacturing and marketing plans in changeable systems facing heterogeneous customers. The model capture the dynamics of both platform technology to manage demand variety and scalability technology to manage demand volume. The approach will help changeable manufacturing managers to decide on the best structure as well as parameters settings for their system facing today's uncertain demand. These decisions include investment in required technology, marketing policies as well as various internal operation plans

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Keywords: Variety; Volume; Dynamics; Manufacturing

1. Introduction

In today's turbulent market the level of demand's uncertainty is continuously increasing. In response, manufacturing system technologies are evolving to address the associated challenges including managing the variation in both mix (variety) and volume in the global heterogeneous demand. Examples of technology advancement employed in changeable systems include production platforms to manage product variety as well as capacity scalability mechanisms to manage volume fluctuations. The complexity of managing changeable systems manifests itself not only in the complicated involved technologies, but also in answering the questions of what is the optimal structure and best parameters'' settings of the considered changeable manufacturing system. Answering this question and thus

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attempting to better manage these advanced systems requires a fundamental understanding of the system's dynamics and the impact of different market and operational parameters on its performance. Such understanding is the main motive behind this work and is summarized in figure 1.

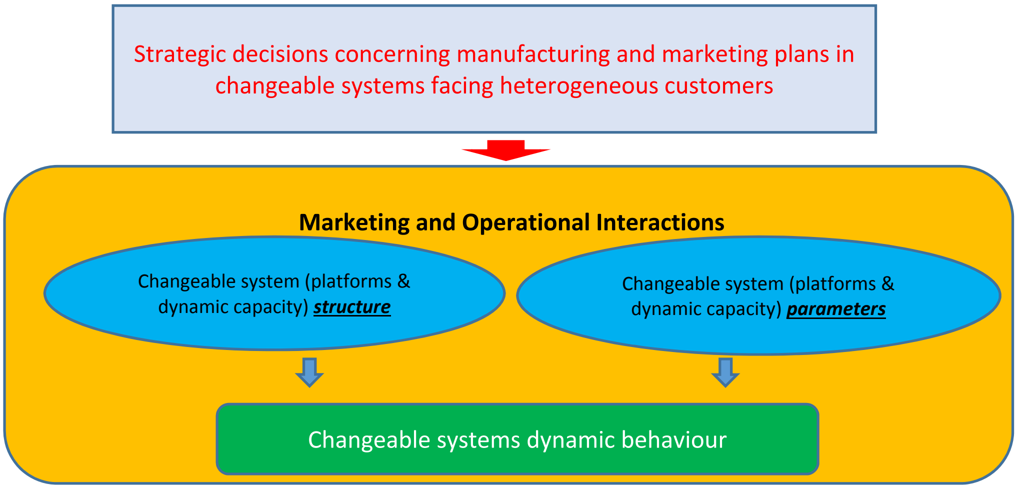

Fig. 1. Managing changeable systems via understanding the structure/parameters dynamics

2. Literature Review

A good review on of technical models and metrics that address product family platforms can be found in [1]. Examples of research work who tried to capture market parameters and their impact on the product line design include Kumar et al. [2] who proposed a market driven product family design approach known as MPFD to integrate market considerations with family design concerns in order to enable product family positioning. This approach examines the impact of variety on different market niches and employs a demand modeling through which impacts of competition in different segments on the market share of each competition can be identified. Michalek et al. [3] optimize the product line for heterogeneous markets at the firm-level; the shortcomings of previous product line optimization models are overcome through the following countermeasures: coordination of positioning and design models, using a Bayesian account of consumer preference heterogeneity, managing product attributes over a continuous domain (in order to avoid complexities of combinatorial optimization), and avoiding infeasible or impossible solutions. A related study by Lou [4] presented a product line optimization method for simultaneously considering important factors from both marketing and engineering domains. When designing the product line, this method considers the strategic reactions of incumbent manufacturers and retailers.

On the capacity scalability side, extensive review of modern scalability problem and its management can be found in [5]. Examples of modeling the dynamics of capacity scalability includes the approach to investigate a new hybrid scaling policy taking into account demand, Work-In-Process (WIP) and backlog levels in single stage production and with uncertainties in multi-stage production was developed in [6] and [7] respectively. Spicer et al. [8] explored the type of the scalability instrument to be employed as well as whether or not to employ scalability as a basis for analyzing alternative solutions. Matta et al. [9] developed a model for managing capacity scalability taking into account various technological preferences the market may require.

Most of the available review on managing both variety and volume failed to integrate both aspects in one model and at the time exploring the dynamics of the different associated parameter including both costs and value created. The model presented in this paper cater for this current gap.

3. System Dynamic Model for Changeable Manufacturing System

A dynamic model for variety and volume management problem in changeable manufacturing systems with its different internal and external parameters has been formulated using system dynamics and is depicted in figure 2

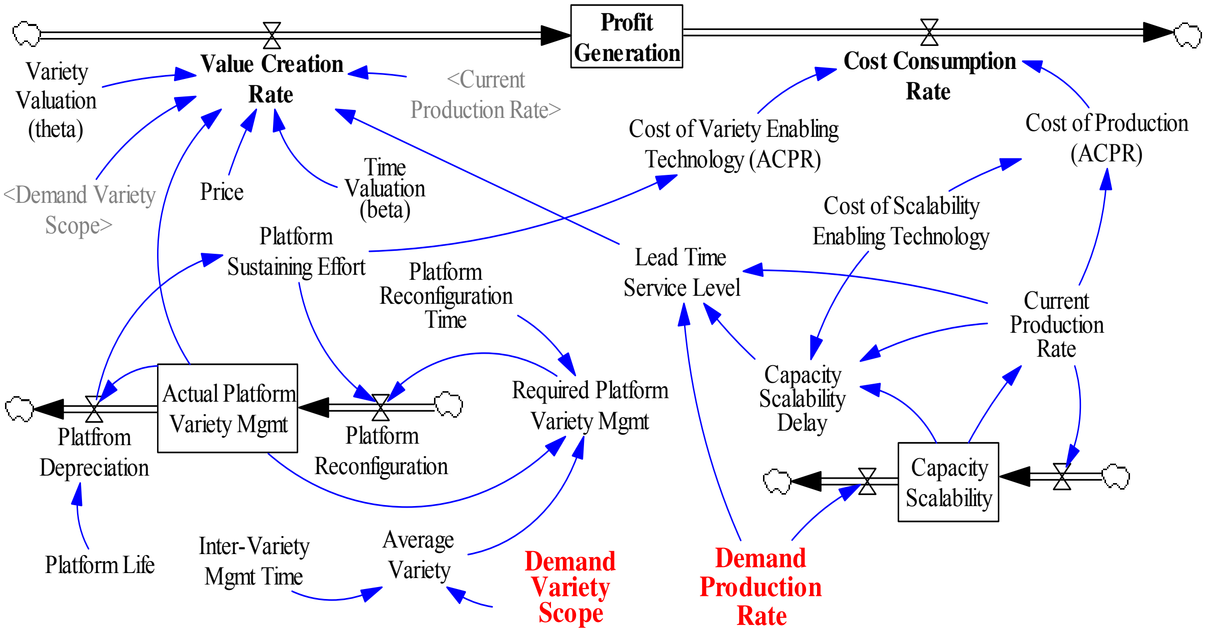

Fig. 2. Dynamic variety and volume management model in changeable system

3.1. Model Notation and Definition

Nomenclature

CCR(t)	Cost consumption rate
CVET	Cost of variety enabling technology
CPR(t)	Current production rate
PUC	Product unit cost
PSE(t)	Platform sustaining effort
LTSL	Lead time service level
CSET	Cost of scalability enabling technology
APVM	Actual platform variety management
RPVM	Required platform variety management
P	Selling price
DPR(t)	Desired production rate
VCR(t)	Value creation rate
CSD(t)	Capacity scalability delay time
DVS	Desired variety scope
CSL	Capacity scalability level
PG	Profit generation
PRT	Platform reconfig time
PL	Platform life

AV	Average variety
PDR(t)	Platform depreciation rate
PRR(t)	Platform reconfiguration rate
DST	Demand smoothing time
ACPR	Activity cost pool rate
β	Customer time valuation parameter
θ	Customer variety valuation parameter

3.2. Model Dynamics

3.2.1: Variety Management System

As mentioned earlier, the modelled system uses reconfigurable product platforms to manage the variety of products. The stream of demanded variety scope (DVS) is used to capture variety demand and is averaged using demand smoothing time (DST) to set the target average variety (AV) that the system will aim to manage (eq. 1):

$$AV = \frac{DVS}{DST} \tag{1}$$

The average variety is further used to determine the required platform variety management (RPVM) level which the product platform will try to achieve using a goal adjustment control approach. The adjustment is based on the difference between the average variety (AV) target and the actual platform variety management (APVM) level and is delayed as function in the platform reconfiguration time (PRT). The platform reconfiguration time reflects the flexibility degree of the employed product platforms have when switching from one product variant to another. Equation (2) shows the modelled goal adjustment approach.

$$RPVM = \frac{AV - APVM}{PRT} \tag{2}$$

The actual platform variety management (APVM) is calculated as the difference between platform reconfiguration rate (PRR) and the platform depreciation rate (PDR) as shown in equation (3).

$$APVM = PDR(t) - PRR(t) \tag{3}$$

Platform reconfiguration rate (PRR) captures the required variety rate and further enhances it with platform sustaining effort (PSE) as shown in equation (4).

$$PRR(t) = RPVM(t) + PSE(t) \tag{4}$$

Platform sustaining effort is an aggregate value that reflects the facility effort to counter the effect of depreciation rate through maintenance, technology changes/upgrades, etc. In this model a simple linear relation is used to relate the platform sustaining effort (PSE) to its depreciation rate (PDR) using the parameter α as expressed in equation (5). The value of the (α) parameter depends on the type of platform employed (scalable, modular or generative). The value of α is assumed to be 1 in this model.

$$PSE(t) = \alpha PDR(t) \tag{5}$$

Platform depreciation rate (PDR) is the rate by which the implemented product platform will depreciate over its platform life (PL) and is affected by the current production and actual performance of the platform (6). The value of PL is related to the product life, technology implemented, investments plans as well as the firm's costing policy.

$$PDR(t) = \frac{APVM}{PL} \tag{6}$$

3.2.2: Volume Management System

The required production volume for each of the products variants is assumed to be equal (same order size). Thus the volume of production managed (number of all product variants) is the aggregate sum of all orders. The current production rate (CPR) is supposed to fulfil the demand production rate (DPR). However, to accommodate for market dynamics, the system is equipped with scalable capacity systems to make up for any discrepancy between both rates through capacity scalability level (CSL). The scaling system calculates that discrepancy as a percentage of the current production rate. This production control mechanism is shown in equations (7 and 8).

$$CPR(t) = CPR(t_0) + CSL(t) \quad (7)$$

$$CSL(t) = \frac{DPR(t)-CPR(t)}{CPR(t)} \quad (8)$$

The scalable capacity is introduced after a capacity scalability delay (CSD) time. In this model, the delay time is modelled as a proportion of the production lead time which is the same proportion of the scaled capacity rate to the current production rate. This dynamic calculation of the (CSD) time will better capture real capacity scaling practices. In addition and to further capture the dynamics of such delay time, (CSD) time is introduced as a function of the implemented scalability enabling technology (SET). The adopted function in this model is consistent with the wide literature which supports that implementing technology can reduce the production time and cost. We follow [10] who showed that this reduction is a multiplicative function of cost of such technology and also the work of [11] who showed that this function can be modelled as square root of cost of such technology per produced part.

It is important to note that this reduction in the delay time using such technology will also come at a cost. Capturing the dynamics of the capacity scalability delay (CSD) time in this manner is essential to our analysis since the overall lead time of production is an integral component in value creation for the customers and this lead time is highly affected by this delay. The capacity scalability delay (CSD) time calculation is shown in equation (9).

$$CSD(t) = \left(\frac{CSL}{CPR(t)}\right)\left(\frac{1}{CPR(t)}\right) * (1 - \sqrt{CSET}) \quad (9)$$

3.2.3: Profit Generation Calculations

As mentioned earlier, in today's customer cantered market, profit generation (PG) should be captured as function of the value generated for the customers. Equation (10) depicts how profit is calculated in this analysis as the difference between the value creation rate (VCR) to customers and costs consumption rate (CCR) associated with such creation.

$$PG = Max(VCR(t) - CCR(t), 0) \quad (10)$$

The coming sections will detail how value creation rate and cost consumption rate are calculated.

3.2.3.1 Value Creation Rate

Parameters θ and β are used to represent the customer's preference on variety scope satisfaction and lead time service level of the required volume respectively. It is assumed that θ and β are stochastic variables with uniform distribution [0,1] i.e. the customer's heterogeneity in the valuation of product variety and lead time is uniformly distributed among all arrivals. This assumption follows a common practice in existing economic literature that models customer income dispersion. Customers make their purchase decisions to maximize their utility of consumption or benefit which is defined as a linear function of the ratio of the actual platform variety management (APVM) and the demand variety scope (DVS) to variety valuation parameter θ and also the lead time service level (LTSL) value compared to the customer lead time valuation parameter β. Any customer who has the desired utility satisfied is willing to buy the product with price (P). The value creation rate that reflects this utility function is shown in equation (11).

$$VCR(t): \begin{cases} If: \ {}^{APVM}/_{DVS} \geq \theta \ and \ LTSL \geq \beta \\ \quad Then: \quad VCR(t) = P * CPR(t) \\ \quad\quad Else: \quad VCR(t) = 0 \end{cases} \quad (11)$$

The lead time service level (LTSL) reflects both the response to the required demand production rate (DPR) and the time required for such response. Satisfying the required volume is captured as a relative measure between the required demand volume and the current production volume and that measure (which ideally should approach 1) is further decreased (penalized) by a value equal to the relative measure between capacity scaling delay time and production lead time (thus the faster the scaling the less the penalty will be). LTSL is calculated in equation (12).

$$LTSL = Max\left[\left[Min\left(\frac{CPR}{DPR}\right), 1\right] - \frac{CSD}{1/_{CPR}}, 0\right] \quad (12)$$

3.2.3.2 Cost Consumption Rate

The cost structure used to calculate the cost consumption rate (CCR) is based on the concept of Activity-Based Cost (ABC) introduced by [49]. Activity-Based Costing estimates the product/service cost by assigning cost to the activities involved in their creation process. Park and Simpson [50] stated that ABC systems are appropriate costing methods for product families and product platforms. These activities can be distributed among produced units or batch or process. In managerial accounting; activity cost pool rate is a set of costs incurred when certain operations are performed within the organization. By accounting for all costs incurred in a specific activity using activity cost pool rate (ACPR), it becomes simpler to assign those costs to products, batch or process.

The cost consumption rate (CCR) is mainly composed of three components. The first component is the product unit cost (PUC) reflecting the pooled cost of materials, labor and other overheads and it is distributed over the produced parts. The second considered cost is pooled over the process of sustaining the product platforms discussed earlier and is referred to as the cost of variety enabling technology (CVET). It is important to emphasize that CVET will be highly affected by the type of platforms used (scalable, modular or generative). The final cost component is the cost accounting for the cost of scalability enabling technology (CSET) and it is distributed over produced parts. Cost consumption rate (CCR) calculations are in equations (13 and 14).

$$CVET(t) = PSE(t) * ACPR_{CVET} \quad (13)$$
$$CCR(t) = CVET(t) + [CPR(t) * (ACPR_{PUC} + ACPR_{CSET})] \quad (14)$$

4. Summary

This paper presented a dynamic model to capture and integrate multiple crucial parameter to better understand and manage variety and volume in changeable manufacturing systems including:

- Heterogeneous demand parameters to reflect the various customers' preferences.
- The dynamics and parameters involved in adopting and managing modern platforms to cater for production of variety of products
- The dynamics and parameters involved in adopting and managing scalable capacity mechanisms to cater for volume fluctuation of products
- Capturing the costs parameters and translating them into value creation rates to better reflect profit in today's market as the difference between values appreciated by the customer and costs associated with their creation.

The next steps will involve multiple simulation of case studies to illustrate the impact of the captured parameters and how they relate to one another. The analysis will be designed to understand the underlying dynamics coupling different marketing and operational policies at different demand scenarios. The presented approach with the next analysis and implementation steps will aid manufacturers employing modern advanced systems to make better decisions while taking into account marketing parameters simultaneously with operation parameters to fulfill the required value perceived by their customers for both demand mix and volume.

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